Design and construction technology for a 15 cm long liquid lithium lens

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Contents

I. Lens design

The lens design (Fig.1) should provide its maximum mechanical firmness under action of static pressure in liquid lithium and a pulse pressure caused by the magnetic field and lithium thermal expansion at the pulse heating of an operation section of the lens (1). Detailed consideration of mechanical tensions in the lens including an analysis of the affect of buffer volumes and compression effects of the lithium cylinder by magnetic field with its possible break off from the titanium shell has been conducted in [1]. It was shown that in order to avoid the latter effect in the system it is necessary to provide the preliminary static pressure of the order of *300 atm* at the field value of *10 T*.

The most crucial component of the lens design is a thin wall titanium cylindrical shell (2) around the heated cylindrical part of the lens and especially its welding points on the ends to the thick wall cylinder (3) limitting the lithium buffer volumes (4) in the current carrying bodies of the lens (5). The current carrying bodies are the basic force elements of the design taking both the radial and longitudinal forces. The radial firmness of the bodies is determined by the thickness of its walls with holes designed for supplying lithium tubes (6) and by long titanium bolts (Pos.11 Fig.1b) providing the longitudinal tightening of the bodies. The tightening bolts take up the forces of lithium static pressure at an area $\pi \cdot r_0^2$ ($r_0 = 1\ cm$ — radius of the lens operation area) and a pulse pressure of magnetic field transferred from the lens operation area to the end plugs (8) with beryllium inserts (9) and appeared in the current carrying gap (9). The pulse magnetic pressure in the current carrying gap (9) is the main source of the construction longitudinal tensions taken up by the tightening bolts (11). The total pressure force is $F_P = P_{r_1} \cdot 2\pi \ln \frac{r_2}{r_1}$, where P_{r1} is magnetic field pressure on radius $r_1 = 1.15\ cm$ corresponding to the surface of ceramics covers the the inner thin wall cylinder, r_2 is outer diameter of the lens body, where current contact is performed. At a current value of $I = 500\ kA$, maximum magnetic field on the lens is $H_0 = 10\ T$ and $P_{r1} = 348\ atm$.

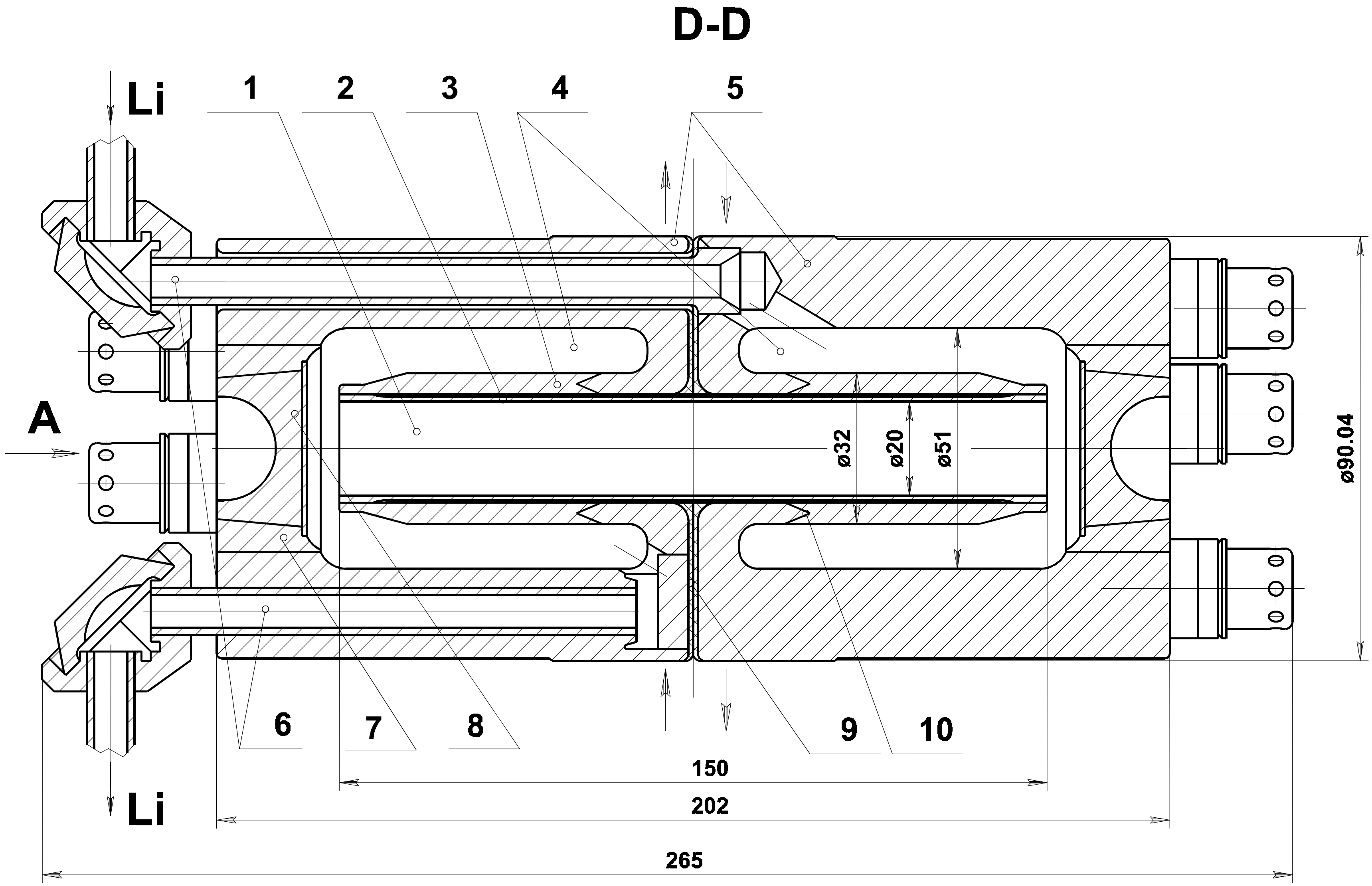

Fig.1a. Lens crossection.
1 – operation part of the lens; 2 – thin wall titanium cylindrical shell; 3 – thick wall titanium cylinder; 4 – buffer volumes; 5 – current carrying bodies of the lens; 6 – lithium supplying tubes; 7 – end plugs; 8 – beryllium inserts; 9 – current carrying gap; 10 – diffusion welding.

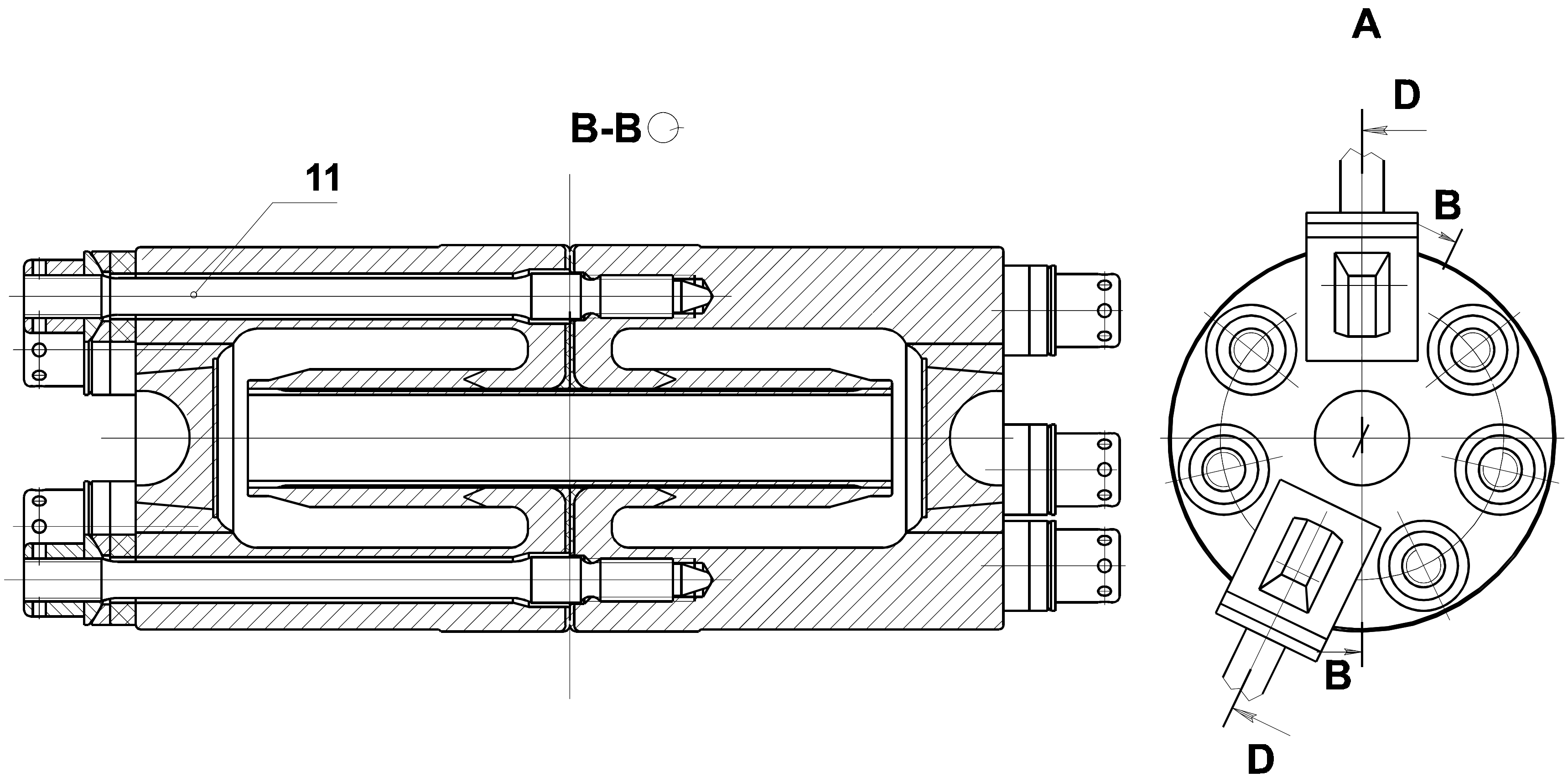

Fig.1b. Lens crossection.
11 – long titanium fightening pins.

Tightening bolts (11) should provide the static compression of two halves of the lens being at different potentials with a force of $F_{st} > F_p$. If $F_{st} < F_p$, the longitudinal motion of current carrying bodies (5) will appear and the force will be transferred to the welding joints of the thin wall cylinder - the lens operation part shell.

In principle, the current carrying bodies can be made to be arbitrarily strong by an increase in the wall thickness and installing any number of tightening bolts providing the longitudinal compression of the lens body. However, the development of the lens **was much complicated by the requirement to adapt it for the power supply from the transformer available at Fermilab.** *"The final design should not require re-design of the Fermilab transformer. Transformer re-design will cost at least $100.00" (Liquid Lithium Lens Review. Author: Stephen O'Day. Date: February 27, 1998 Review Recommendations).* This requirements have limited the value of the lens body outer diameter by *90 mm* to be equal to the inner diameter of the contact clamps (2) connecting the lens with the transformer body (Fig.2). In this case, the radial thickness of lens body turns to be equal to $h_k = 33.5$ *mm* ($h_k = 90/2 - r_0 - h_{en} - h_{cer}$, where $h_{en} = 1$ *mm* is the titanium shell thickness, $h_{cer} = 0.5$ *mm* is the thickness of ceramics). The value $h_k = 33.5$ *mm* is taken by: wall thickness of thick wall titanium cylinder (3 Fig 1a) $h_c = 5$ *mm* on which through ceramics a thin wall shell supports; the radial size of the buffer volume (4) $h_b = 10$ *mm* and a thickness of the current carrying body (5) $h_{cap} = 18$ *mm* with holes of *10.4 mm* in diameter which the tightening bolts (11) passed through. Thus, an ultimate diameter of the lens body limits also both the desirable increase in the lens buffer volume and diameters of tightening bolts determining the construction longitudinal firmness.

Both these factors put the limit on the ultimately accessible magnetic field and reliability of the lens operation.

In addition, the contact connection between the transformer contact clamps (Pos.2 Fig.2) and either stainless steel (or titanium) body of the lens heated up to the temperature value of $250\,^{\circ}C$ limits the reliability of the long term operation of the contact connection. According to the contract between the BINP and FNAL the lens under development should be operated reliably at a field of *10 T*.

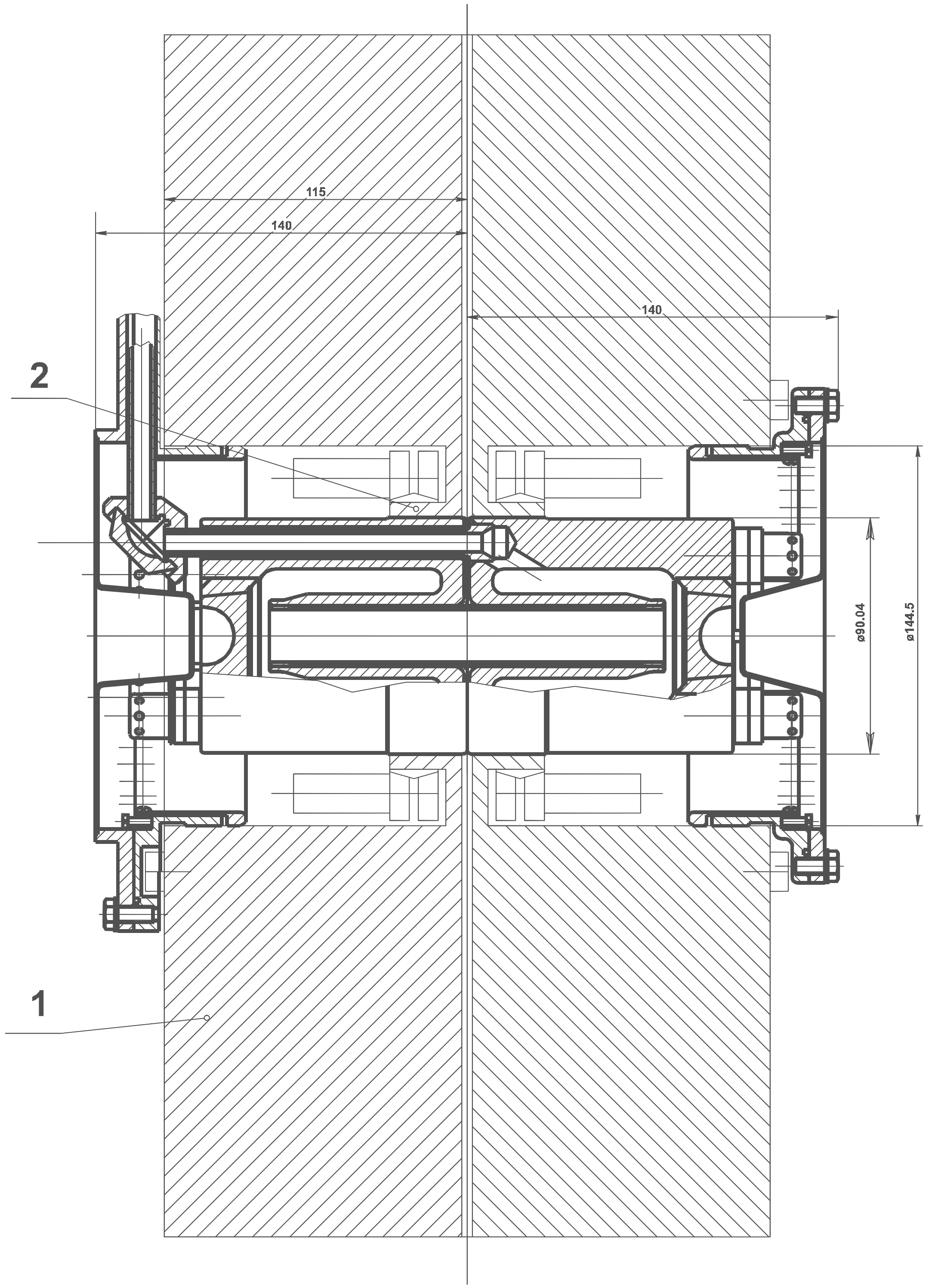

Fig. 2. Lens with Fermilab transformer .

1 – transformer; 2 – contact clamps.

«This accord concerns the design, manufacture and testing of liquid lens with the same geometrical parameters as present FNAL antiproton solid lithium collection lens: 15 cm length and 2 cm diameter. To further lithium lens technology, a goal of reliable operation at 10 T for 10 million pulses is proposed. If this proposal is accepted, this goal will manifest itself in the form of short term testing a higher gradient. The prototype to be built at the Budker Institute of Nuclear Physics would be tested for one million pulses at 13 T in phase 3 of the text below.» (Accord, page 1).

However, if the geometrical limits given above are removed, one can provide a higher mechanical firmness of current carrying bodies and achieve their more reliable compression in longitudinal direction. Then with this lens one can carry out very important studies of the possibilities to raise the field up to *15-17 T*. Therefore, in the lens power supply system it was envisaged large spare capacity in energy and a possibility to raise current up to *1 MA* corresponding to maximum field of *20 T* at the lithium cylinder surface. The lens construction firmness was increased correspondingly (Fig.3a). The manufacturing technology for current carrying bodies of fully titanium was developed. This enabled us to avoid the diffusion welding of thick wall titanium cylinders with stainless steel bodies of current carrying bodies used in the construction Fig.1a, 1b, (10 in Fig. 1a) and to increase the radial firmness of cylindrical part by a factor of 2.5.

In the new design, the bases of bodies of the lens transforms into the current carrying disks (1 in Fig.3a) with welded copper collet contacts (2) connecting the lens to the inner cylindrical surface of the transformer. The BINP transformer intended for the lens test has an inner diameter of *150 mm*. The transformer available at FNAL (Fig.3b) can get such a diameter with a simple modification by cutting off the available contact clamps (position 2 in Fig.2). Thus, the area of the contact connection at a diameter of *150 mm* will be 1.7 times larger than that in the previous design and the contact will be achieved on the cooled surface of the transformer body. In the gap obtained between the lens body and transformer of *30 mm* 12 titanium bolts of *10 mm* in diameter are placed to provide an additional longitudinal compression of the lens. If necessary, such a lens can easily be transformed to the design given in Fig.1 in order to meet completely the requirements of Accord.

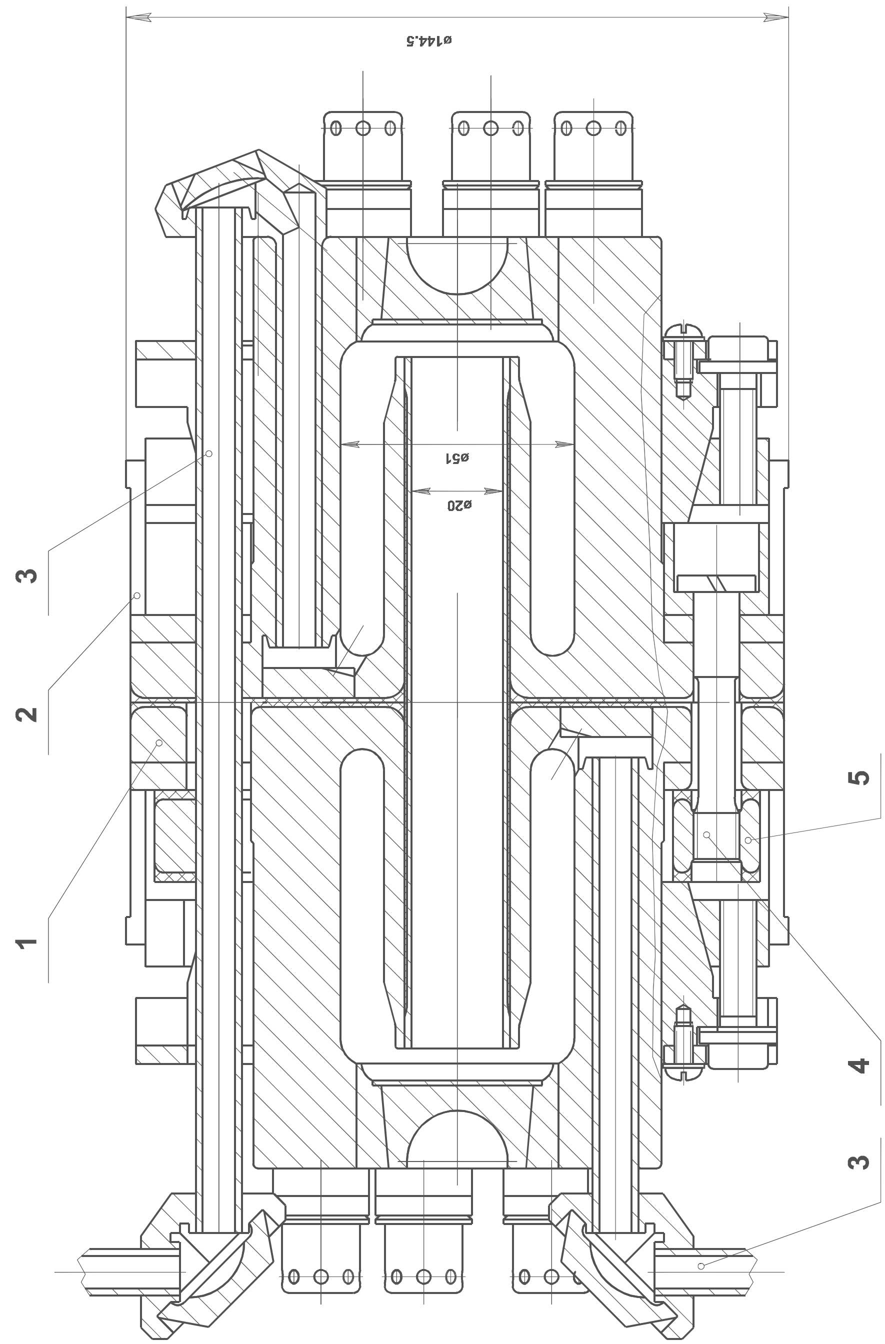

Fig. 3a. New design of the lens.

1 – current carrying disks; 2 – collet contact clamps; 3 – lithium supplying tubes; 4 – tightening bolts; 5 – ceramic coated disk

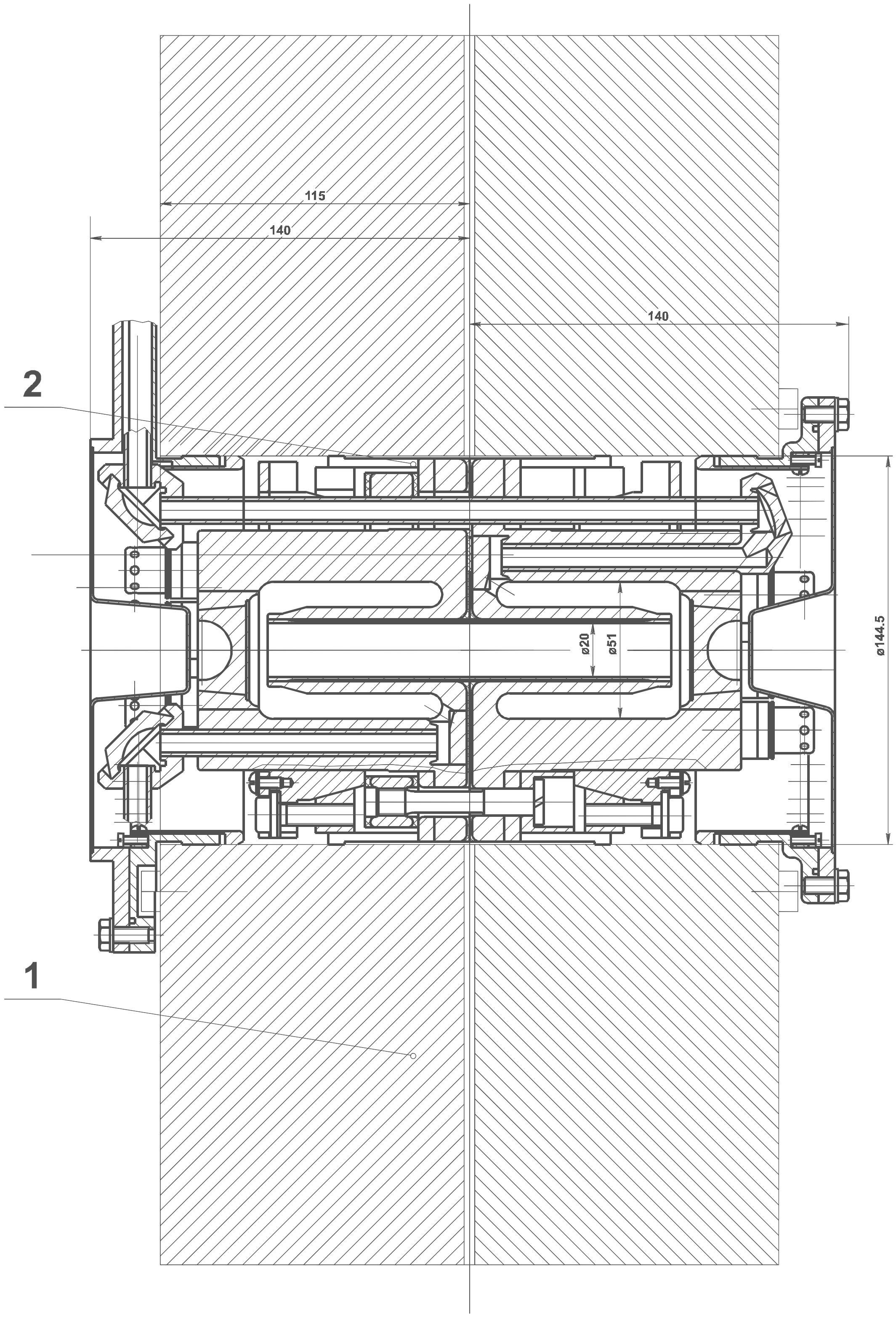

Fig.3b. New lens with Fermilab transformer.

1 – transformer; 2 – collet contact clamps.

If one can provide an absolutely rigid longitudinal compression of the lens bodies, the only source of stresses in the weld end joints of the thin wall titanium shell of the lithium cylinder would be its longitudinal thermal expansion at the lens pulse heating. These stresses are the basic limit of the shell long term operation. With the shell heating up to temperature ΔT at the points of its rigid welding the compression stresses $\sigma = E \cdot K \cdot \Delta T$ will occur where $E = 1 \cdot 10^{6} \dfrac{kG}{cm^{2}}$ is the modulus of titanium elasticity, $K = 8{\cdot}10^{-6}$ is the coefficient of its thermal expansion. The shell heating occurs in two stages. When passing through lens a fraction of the current pulse goes along titanium causing the fast pulse heating of the shell up to temperature $T_{Ti} = T_{Li} \cdot \dfrac{\rho_{Li} \cdot c_{Li} \cdot \gamma_{Li}}{\rho_{Ti} \cdot c_{Ti} \cdot \gamma_{Ti}}$. In order to reduce the fraction of current branched to titanium and pulse heating value to their minima the shell is made of the VT-6 titanium alloy with maximum specific resistance $\rho_{Ti} \approx 140 \cdot 10^{-6}\ Ohm \cdot cm$.

At the specific resistance of liquid lithium $\rho_{Li} \approx 40 \cdot 10^{-6}\ Ohm \cdot cm$ the titanium heating is $T_{Ti} \approx 0.2 T_{Li}$

At the lens surface field of *10 T*, the lithium pulse heating is $\Delta T \approx 70^{o}$ and it grows quadratically with an increase in a field. In this case, the titanium pulse heating is $\Delta T \approx 14^{o}$ and mechanical stress occured in a shell does not exceed $\sigma \approx 150\ kG/cm^{2}$ However, after the fast pulse heating similar to thermal shock the titanium temperature will grow due to thermal conductivity up to the lithium temperature. This heating will result in the stress raise up to $\sigma \approx 400\ kG/cm^{2}$. With an increase in the field even up to *20 T* these stresses can not reach those ultimately admissible for titanium fatique stresses during the tens million cycles of the lens operation.

II. Lens manufacturing technology

1. Manufacture of a thin wall titanium pipe – lithium cylinder shell

The pipe geometry is given in Fig.4. The choice of pipe material and technology of its production are determined by the reliability of lens operation. The reliability factors are the following:

1. Chemical resistance to the flowing melted lithium.
2. High specific ohmic resistance of material.
3. Mechanical firmness under conditions of a multi-cycle sign changing load at temperature $T = 250^{\circ}C$.
4. Good weldability with current carrying components.
5. Good adhesion to the thermal resistant and radiation resistant coating of the aluminum oxide — Al_2O_3 .

On the basis of these requirements and results of experiments performed in 1977 – 1982, [2] the pipe material was chosen to be VT–6 titanium alloy of a mixed structure ($\alpha+\beta$) with the following main parameters:

chemical composition –

Al – 6.25%, V – 5%, Ti – 88.75%;

mechanical characteristics:

Linear expansion coefficient	$\alpha=8.41\cdot10^{-6}$;
Firmness limit	$\sigma_V=90 \div100\ kG/mm^2$;
Yield limit	$\sigma_T=80 \div90\ kG/mm^2$;
Fatique firmness(10^7 cycles)	$\sigma_{01}=30\ kG/mm^2$;
Eectric characteristics	
Specific electrical resistance	$\rho=140\cdot10^{-6}\ Ohm\cdot cm$.

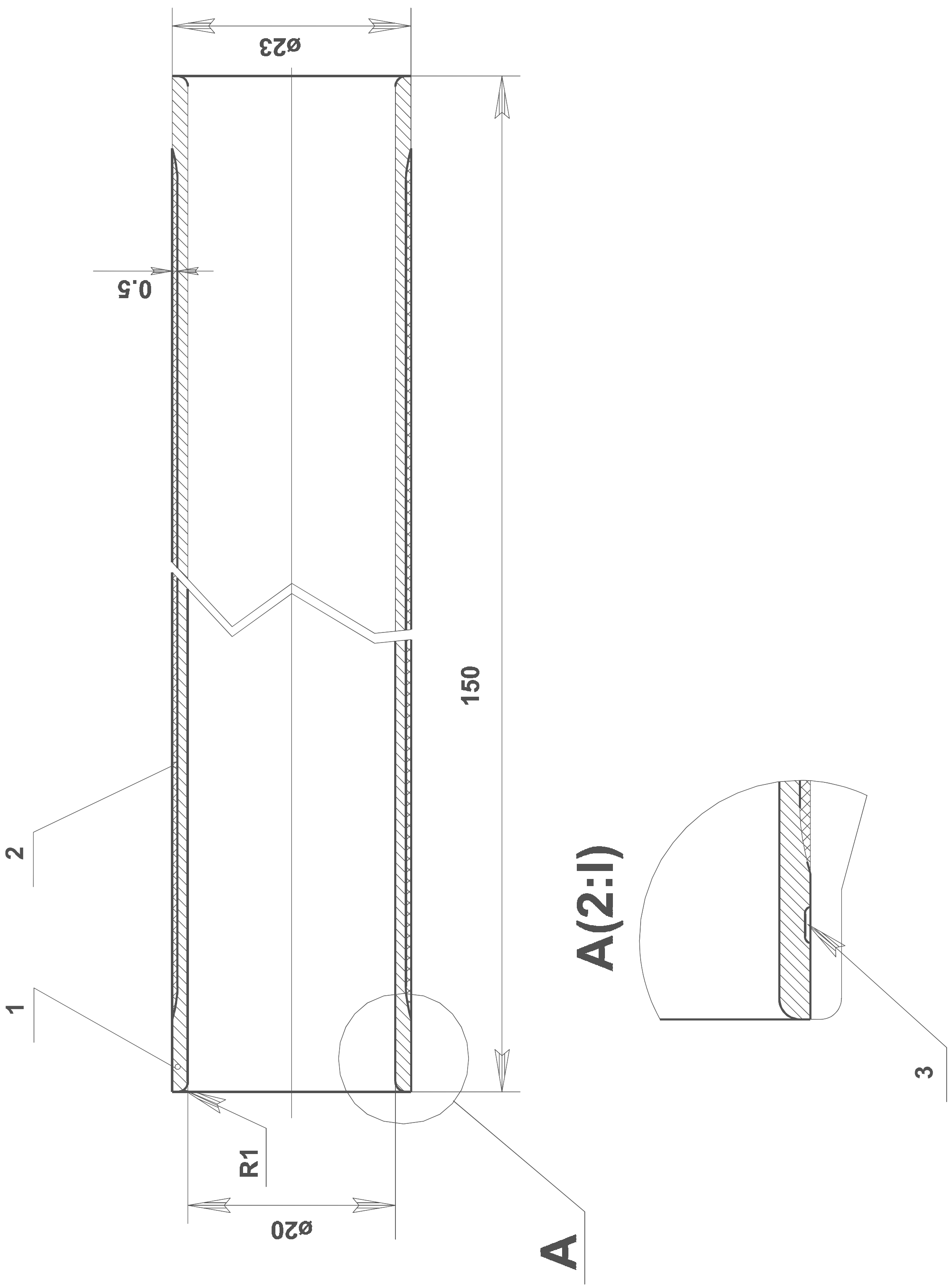

Fig. 4. Thin wall titanium pipe-lithium cylinder envelop.

1 – titanium pipe; 2 – ceramic coating; 3 – ring grove.

An outer surface of the pipe (except for the welding ends) is coated with the thermal- and radiation resistant isolation of Al_2O_3 (Fig.4) by means of the gas detonation coating method described below. In order to remove some possible mechanical stresses between the titanium and ceramics caused by different coefficients of thermal expansion which can result in some cracks and distortions, the outer surface of the pipe is coated by a 10–20 μ thick separating layer of soft Nickel alloy acting as a compensator of mechanical stresses. After laying the nickel sublayer and ceramics layer the outer ceramics surface was then processed with diamond grinding.

The pipe inner surface requires high accuracy of machining (absence of scratches and deteriorations) which can cause the concentration of mechanical stresses and decrease in the cyclic fatique firmness. The final machining of the inner surface with a class of cleanliness of $\nabla 11$ was achieved with a specially made instrument - a special reamer made as a stiff nitride Bohr rod with an odd number of cutting edges.

Technological sequence of the pipe manufacturing is shown in Fig.5:

1) preliminary blank with clean machining of its inner surface;
2) mandrel for mechanical machining the pipe outer diameter prior to apply the ceramics coating;
3) pipe on the mandrel prior to mechanical machining in centers;
4) a set coated by isolation prior to diamond grinding.

The final form of the pipe after its grinding is shown in Fig.4. An additional ring groove pos.3 in Fig.4 puts the limit on the depth of welding by an electron beam and on the formation of the inner meniscus between the welded details (the meniscus decreases the stress concentration in the welding joint).

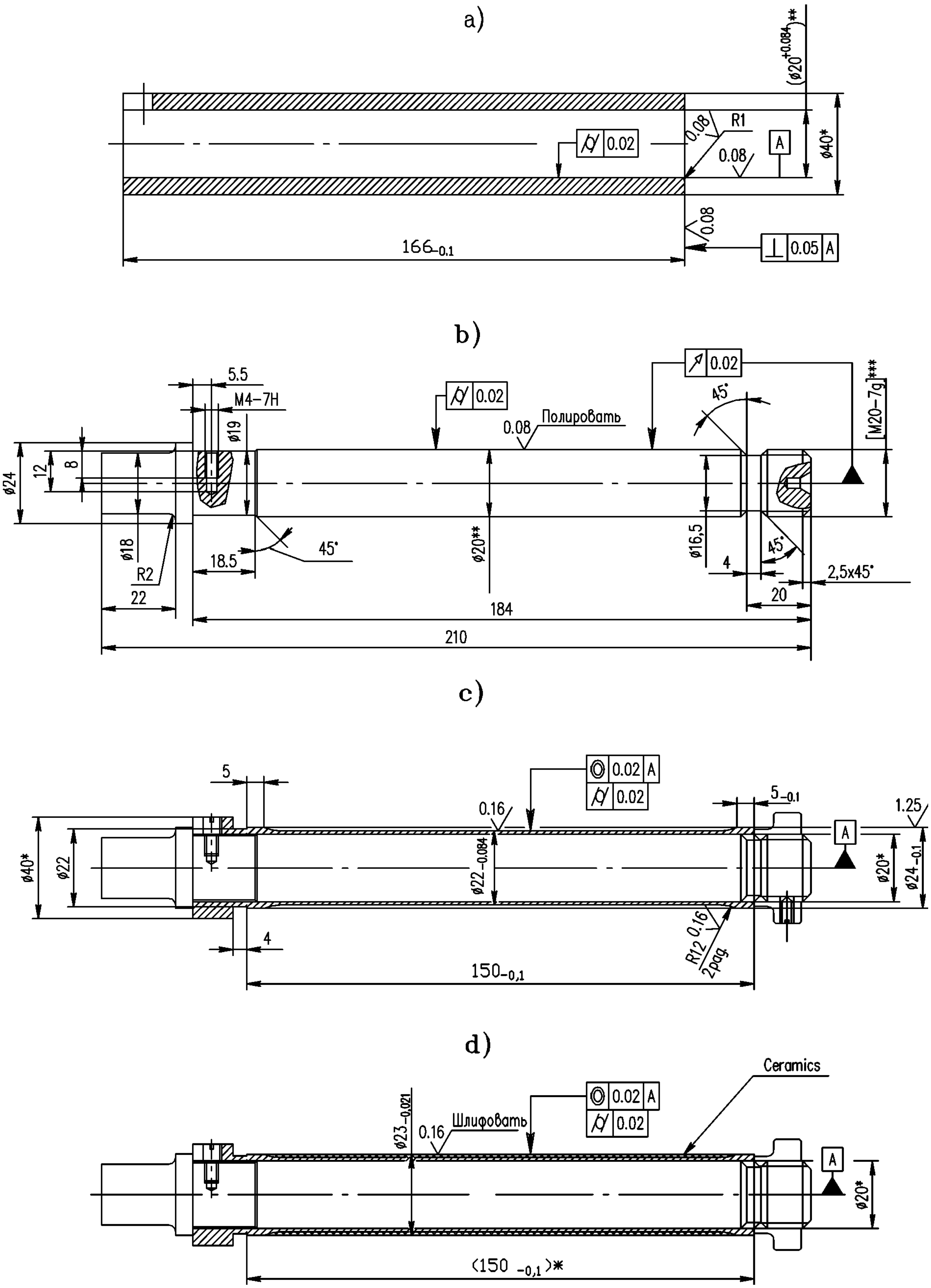

Fig. 5. Technological sequence of one pipe manufacturing

2. Manufacture of lens current carrying bodies

The lens current carrying bodies (Fig.6) are the main power components of the structure.

Two versions of body manufacture have been developed: of the stainless steel 12x18H10T and of the VT-6 titanium alloy. The first version of the body manufacture of stainless steel was chosen due to quite simple technology of the stainless steal treatment and welding. However, in order to provide maximum reliability of the electron-beam welding of the ends of the central thin wall shell (Pos.2 in Fig.1) to the ends of the central thick wall cylinder (3) limiting the buffer volumes in the lens bodies, the latter is also made of titanium and it is connected to the lens body by the diffusion welding (Pos.10 in Fig.1a,b).

The diffusion welding regime was elaborated on a sample given in Fig.7a. The details were welded in vacuum oven during 13 minutes at temperature $T = 850\,^{\circ}C$ and at a compression force of $F = 800\ kG$. The welding joint (1) reliability was checked by applying oil at high pressure into the oil cavity (2). The joint was destroyed at a pressure $P = 500\ atm$ at a breaking load of $F = 2000\ kG$.

In the second version of the structure, the lens bodies were made of titanium thus enabling one to avoid the use of diffusion welding and increase substantially the mechanical firmness of the bodies in the radial direction. In this case, the treatment of the buffer cavities (2 in Fig.6) has been done with the use of special tools shown in Fig.7b. For welding the lithium supplying pipes (4) an electric–arc welding in a inert gas was used.

In both versions of lens manufacture the copper current carrying disks (5) (for the contact of the lens to transformer) were soldered to bodies with silver alloy in vacuum. After the completion of all welding and solder operations the bodies end surfaces were subjected to the precise mechanical treatment and then coated with ceramics by the gas explosive spray method described below.

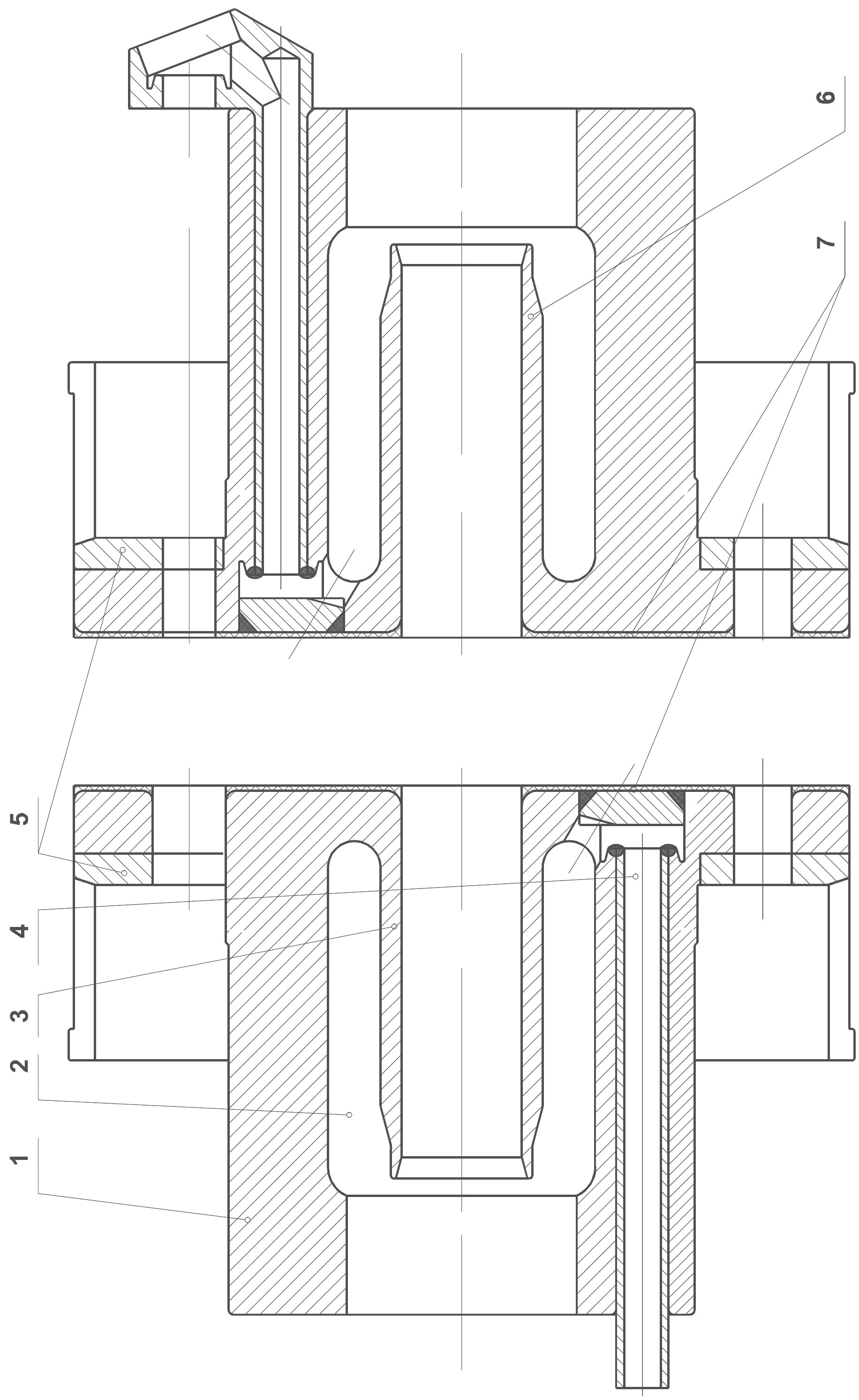

Fig. 6. Current carrying bodies.

1 – lens body; 2 – buffer volumes; 3 – thick wall titanium cylinder; 4 – lithium supplying tubes; 5 – copper current carrying disks; 6 – inner surface of central hole; 7 – ceramic coating of the lens body ends.

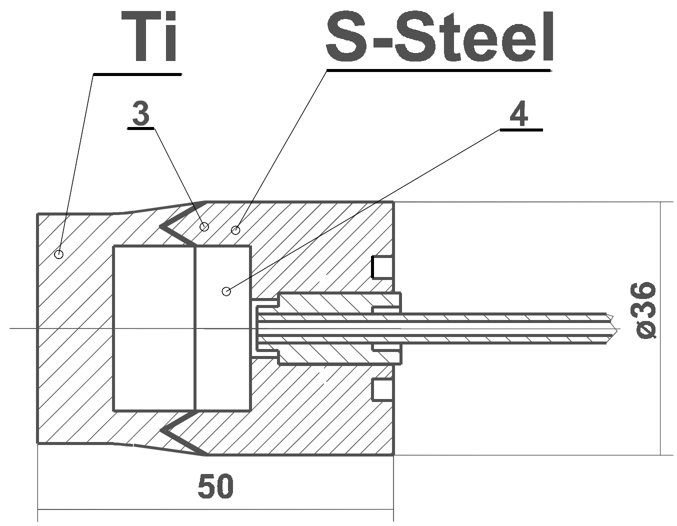

Fig.7a. Sample for diffusion welding.

1 – diffusion welding; 2 – oil cavity.

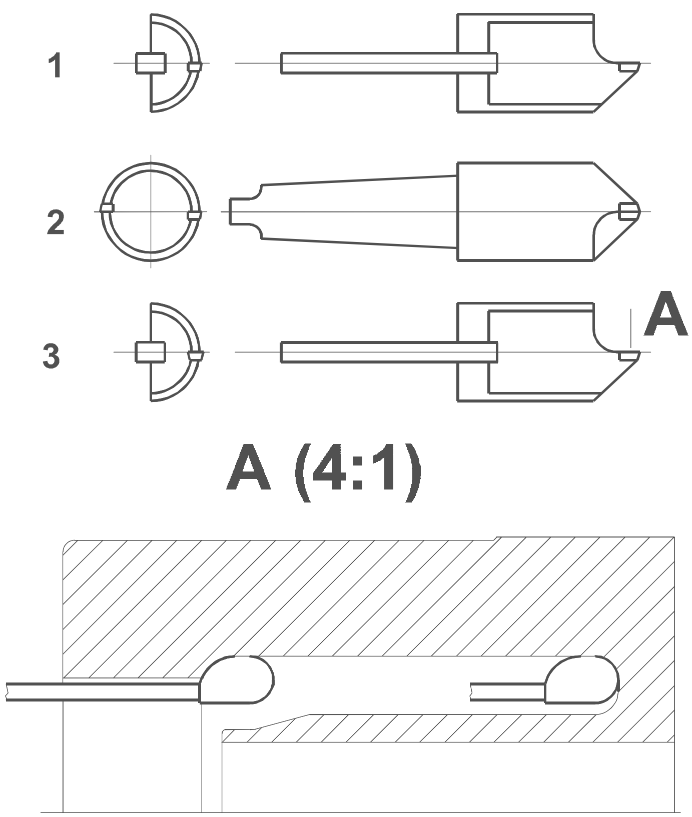

Fig.7b. Special tools for buffer cavities treatment.

After applying ceramics, the body surfaces (7) were machined with diamond instrument and after that, the inner surface (Pos.6 in Fig.6) of central hole was subjected to precise treatment providing rigorous perpendicularity of the end surface and hole axis as well the exact correspondence of its diameter to an outer diameter of the ceramics coated pipe.

3. Ceramics insulation of a lens

The ceramics insulation of the central pipe (2 Fig.4) and the end surfaces of current carrying bodies (pos.7 in Fig.6) is quite crucial component of the lens structure determining both the manufacturing technology and the reliability of its operation.

Main requirements to the lens insulation are the following:

- high mechanical firmness under conditions of high thermal loads during the lens manufacture (welding, annealing, etc.) and at its operation in the regime of cyclic thermal loads and temperature gradients;
- electric firmness at operation pulse voltage $U = 500\ V$;
- radiation resistance;
- good adhesion with construction materials.

On the basis of all said above for the development of electrical insulation of the explosive-gas spraying of ceramics method developed at the Institute of Hydrodynamics Siberian Branch of Russian Academy of Sciences and introduced into industry by the firm «Adhesion» was used.

The essence of the method is the following. For applying the coating a special device the so–called explosive gun is used having the closed from one end water cooled barrel filled in with an explosive mixture and a dose of the powder to be sprayed. After ignition of the mixture with an electric spark the detonation occurs in the barrel. The flow of explosion products with a velocity of $V = 1.5\ km/s$ and temperature of $T = 4000\,^{\circ}C$ heats the powder particle up to melting temperature and throws them onto the surface of detail placed in front of the barrel open end. During the interaction of powder particles with the detail surface a mircowelding occurs and powder particle bonds strongly (on molecular level) to the surface of detail. Then the burrel is blown off with the nonflammable gas and the whole process is repeated. A $10\ \mu$ thick coating is formed per one shot (picture of the installation with a detail Fig. 8 a,b,c).

In order to make the final choice of the method for applying the insulation coating the following tests have been done.

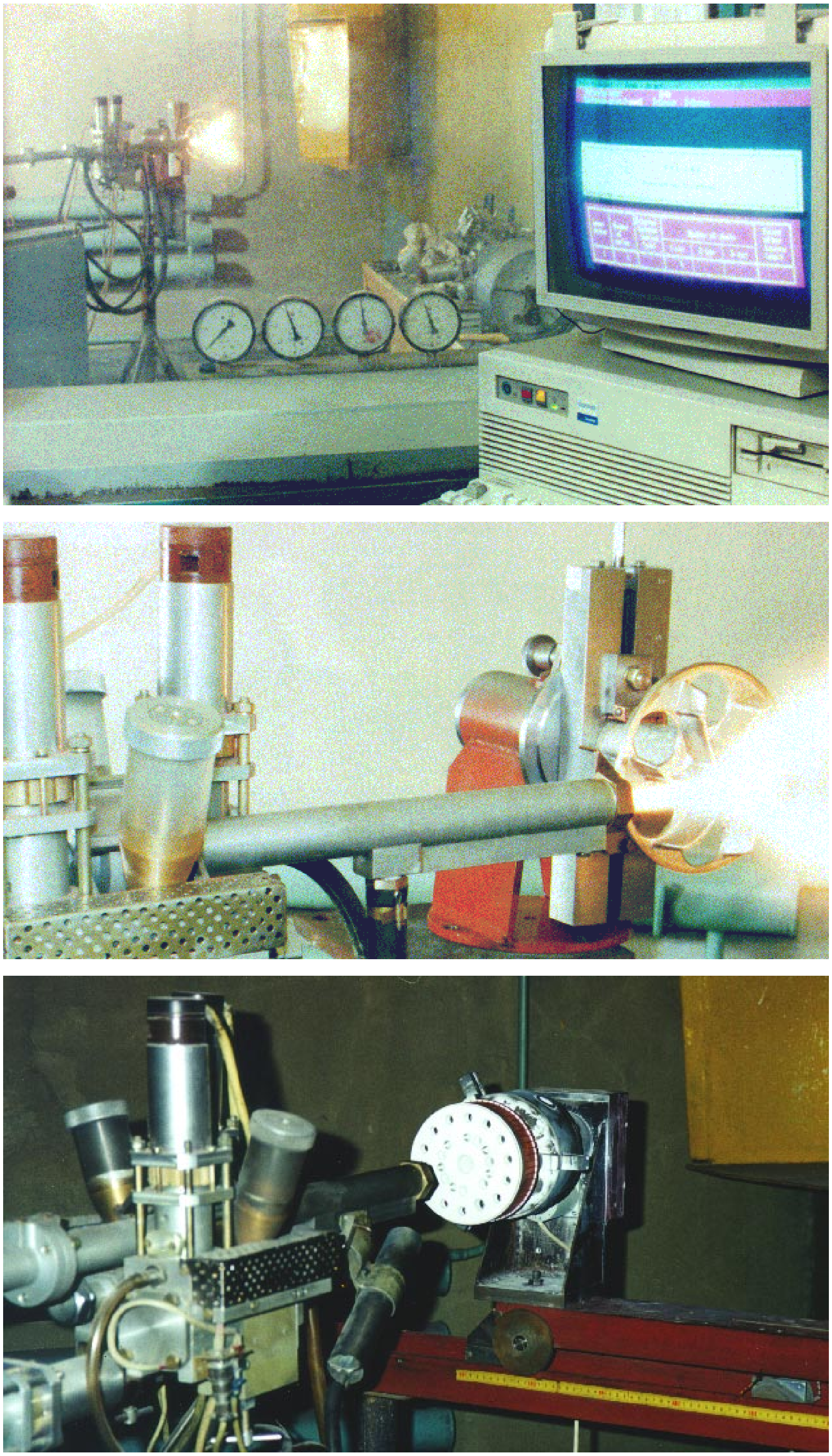

Fig. 8a,b,c. Installation of explosive-gas spraying of ceramics.

1) Electric tests.

A *0.5 mm* thick of Al_2O_3 coating was applied to the pipe with an outer diameter *D = 22 mm* and an inner diameter *d = 20 mm* and on a plate *30x30x1 mm* and then by the diamond grinding the coating was reduced to *h = 0.2 mm*. Then the break-down test was performed with voltage at many points of the ceramics coated pipe and plate with voltage by the steel rod with bending of *R = 2.5 mm* (Fig. 9 a,b). The break down voltage is *U = 3÷4 kV*.

2) Thermal tests.

The samples given above have been subjected to the thermal shock of a few tens cycles by putting details into liquid nitrogen. After reaching temperature of liquid nitrogen on *T = –196°C* the details were quickly immersed into boiled water (*T = 100°C*). After this process, the break-down tests have been conducted on the nondestroyed earlier surface. The break–down voltage reduced down to *U = 2÷5 kV*.

3) Vacuum annealing tests.

With an account for the fact that after welding titanium details it is required an annealing for removing stresses, the Al_2O_3 coated samples of the size given above were subjected to vacuum annealing. The vacuum oven temperature was increased up to *T = 850°C* in 2 hours and then decreased down to *T = 50°C* during 12 hours (characteristic time of oven cooling). The ceramics is dimmed somehow but no defects or cracks (peelings) have been found out. The break-down tests did not reveal any distinguished changes.

After carrying out tests, the final decision was made to produce the insulation with this method.

Thin wall titanium pipes (Fig.4,5) and ends of the current carrying bodies (7 Fig. 6) have been coated by a *0.8÷0.9 mm* thick layer of ceramics and then with the diamond grinding the layer was reduced to the thickness *h = 0.5 mm*. Holes in the lens body for pins have also been coated with ceramics during the pass of plasma jet through the holes.

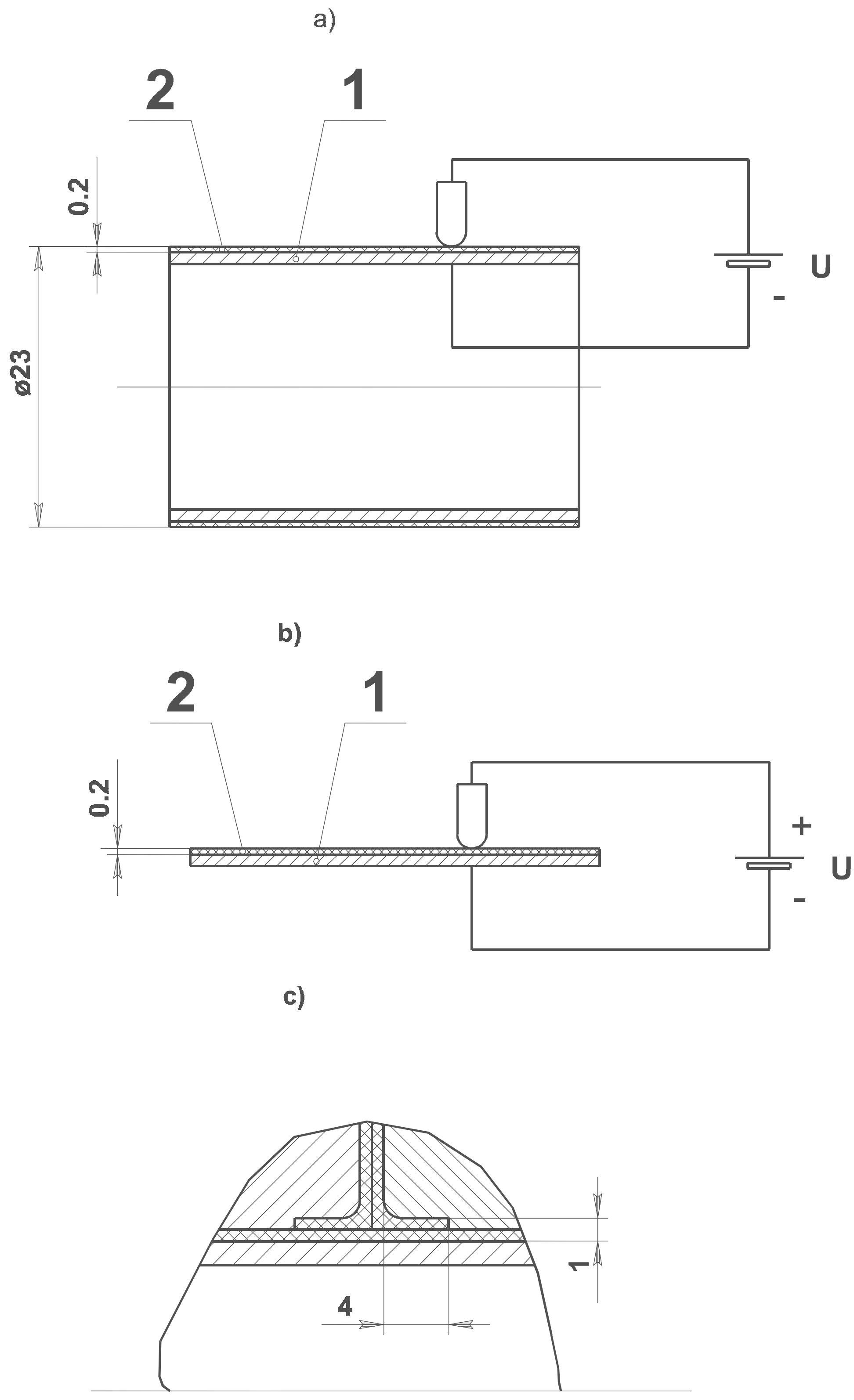

Fig. 9. Samples for electric tests of the ceramic.

The most crucial point (with respect to break-down) in an assembled lithium lens is the middle part of the pipe along the line of intersection of the pipe envelope and contact surface of current carrying bodies.

In order to lower the risk of electric break-down the following technological solution was taken. The shift from the cup surface to the cylinder was made with a small radius and an increase in the hole diameter by $\Delta = 1\ mm$ and a depth $L = 4\ mm$. Further, the ceramics was grinded down to required size. This procedure eliminated the ceramics sliding at the joint (Fig.9c). Figures 10a-f shows the pipes and bodies in the process of treatment and in their final state.

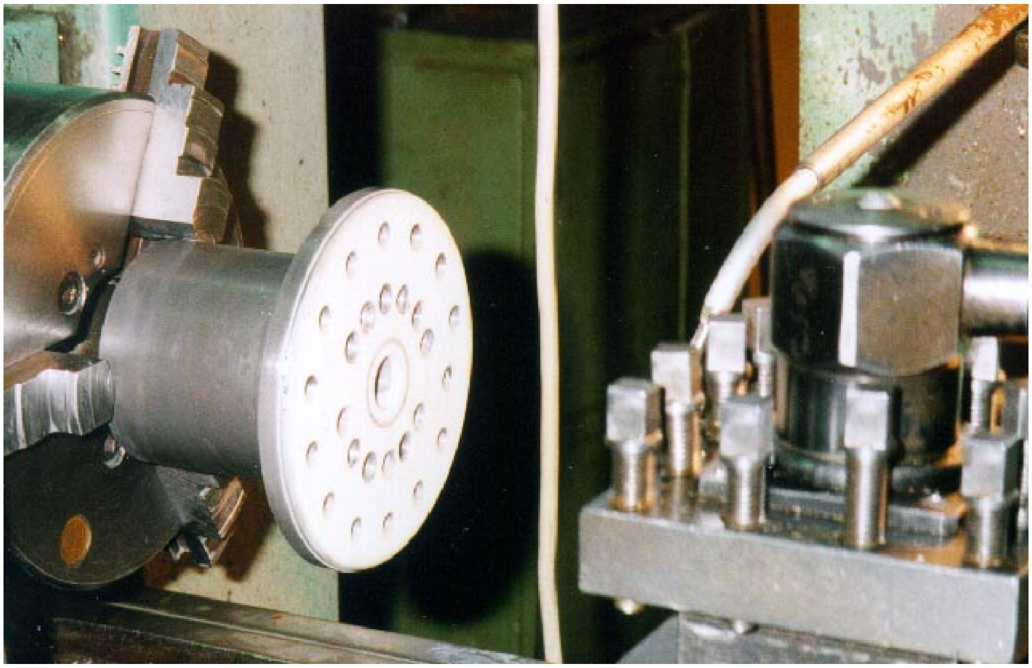

Fig. 10a,b. Treatment of the ceramics surface of the lens body

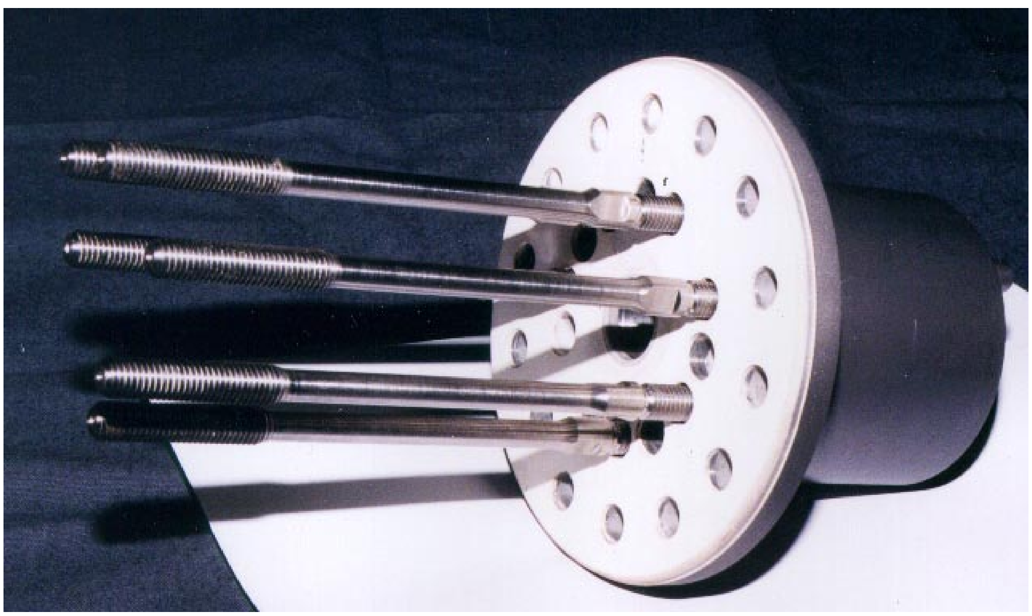

Fig. 10c,d. Pipes and lens body in their final state

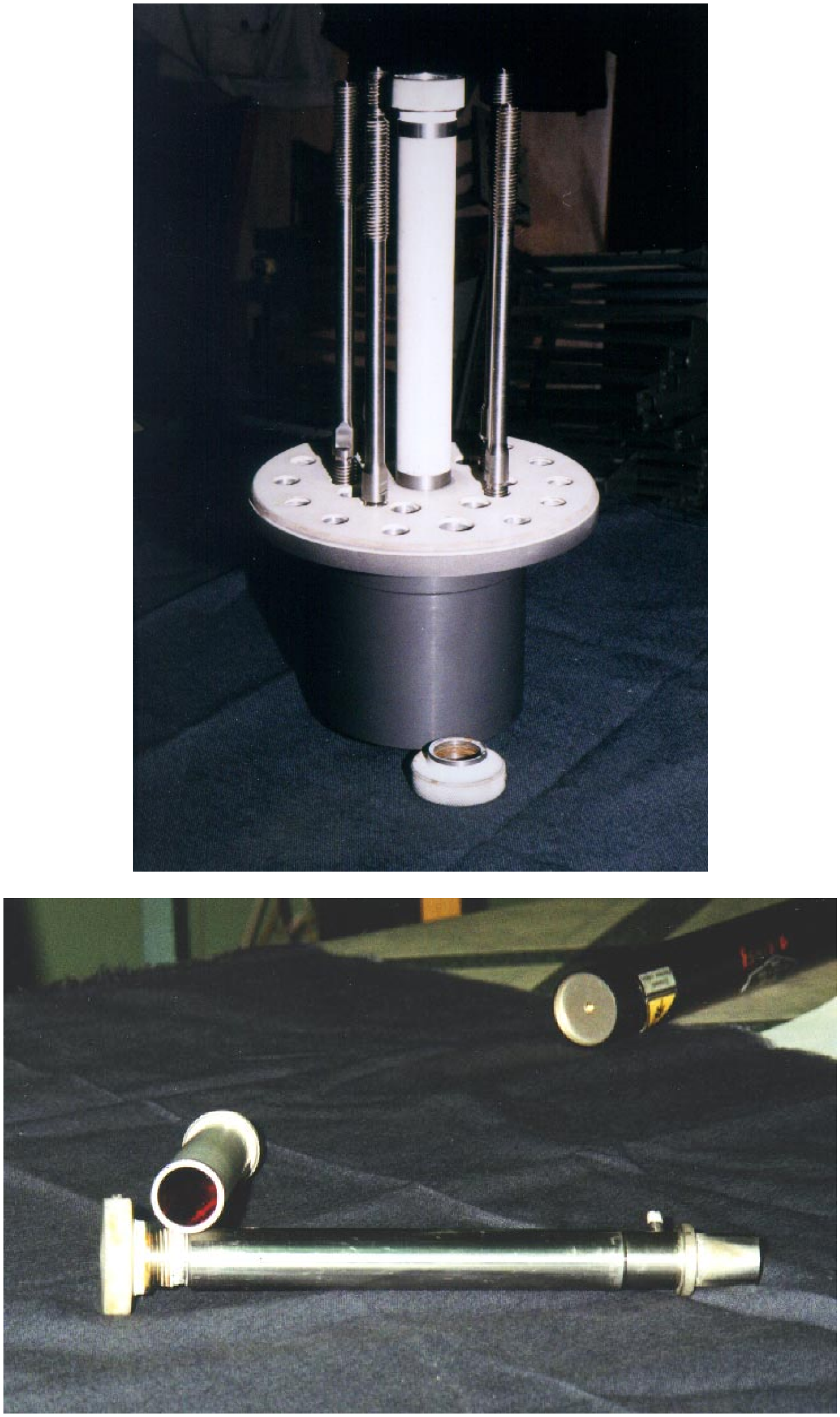

Fig. 10e,f. Pipes and lens body in their final state

4. Lens assembly and welding

The lens assembly is performed in several stages.

1) Lens assembly for welding

After the precise treatment of the ceramics coated lens bodies the long titanium pins (pos.11 in Fig.1b) are screwed into the lens bodies (Photo in Fig.11). Then, bodies with pins are put tightly onto the central pipe with a preliminary heating of up to $300^{\circ}C$. Bodies are tightened with bolts in axial direction (pos.4 in Fig.3a) with the use of the ceramics coated disk (5). In this case, long titanium pins remained free. In this state, the lens is ready to an electron-beam welding of the central pipe ends to the thick wall titanium pipe of the body.

2) Electron-beam welding.

An electron-arc welding device of the INP workshop is given in Photo Fig. 12a. The product of the size up to *1.5 m* can be put into the device vacuum chamber. An electron energy is *60 kV*, beam current is up to *1 A*. The device is equipped with a computer controlled motion of the welded product, current and electron beam focusing. Photo Fig. 12b shows the lens in the process of its installing for welding.

Prior to perform an electron-beam welding of titanium pipes the technology work out and selection of welding regimes have been done on special samples.

First, the welding regime (electron beam current and sample motion velocity) worked out on the flat samples of a few pairs of *1.5 mm* thick titanium plates with different geometry of welding points. For finding out the influence of ceramics on the welding process the Al_2O_3 ceramics was place on one pair of plated directly at the welding region.

Fig. 11. Photo of the lens bodies before assembling

Fig. 12a. BINP workshop electron-beam welding device

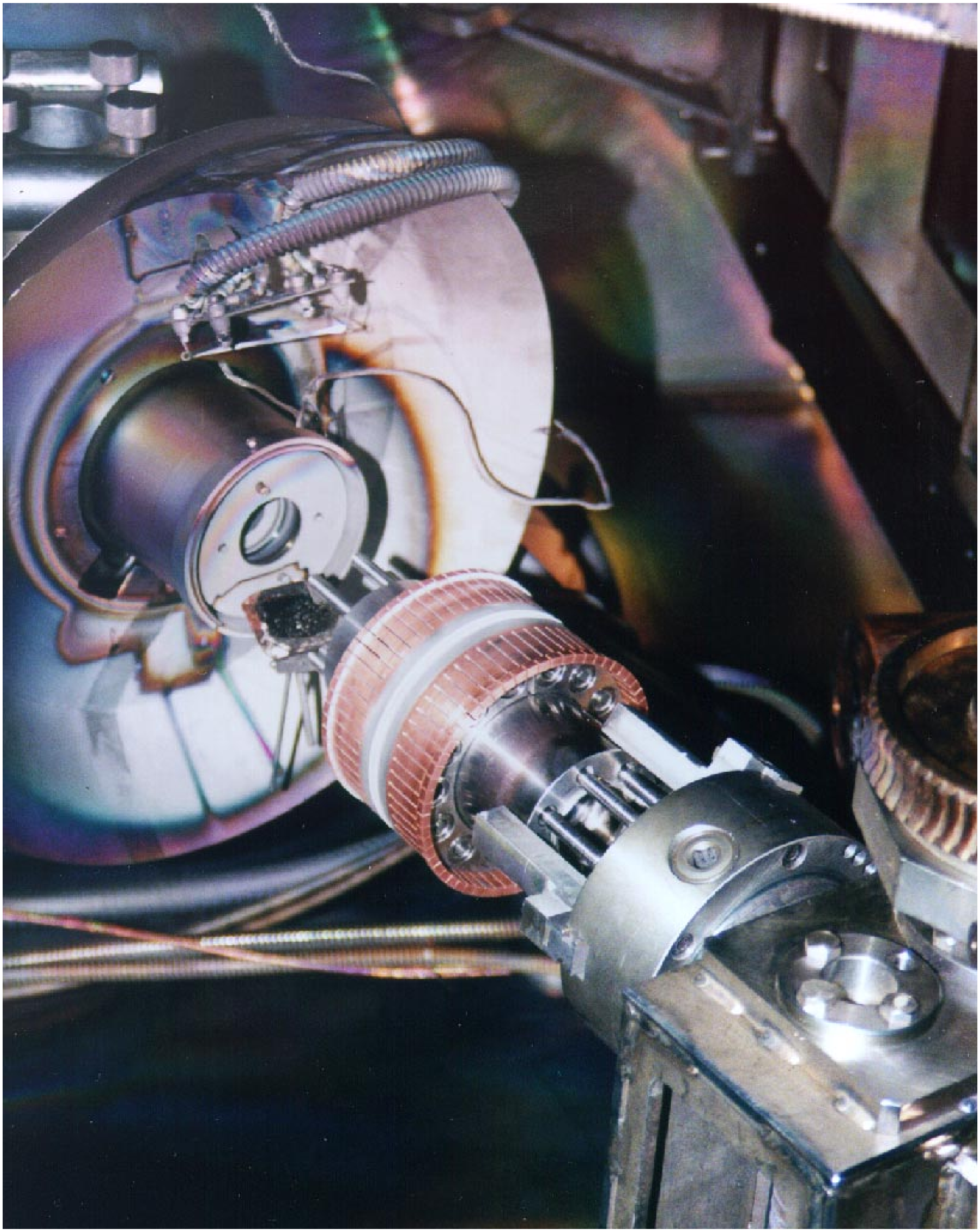

Fig. 12b. Photo of the lens in process of its installing for welding

For the final choice of welding regime a special sample exactly similar to the lens end geometry was produced (Fig.13a). Bolts (3) screwed into the sample simulate the long titanium pins protruded from the lens. A thin wall titanium pipe (2) is ceramics coated by the explosive-gas spray method. After welding, the sample was tested with the oil inner pressure according to the scheme given in Fig. 13b. At pressure $P = 1450\ atm$ botlts (of $8\ mm$ in diameter) were broken. The cut stress in the welding junction reached $= 1850\ kG/cm^2$. In further test on the press, the force $F = 3000\ kG$ was applied to the cup from the external side and the welding was destroyed.

3) Welding of end plugs and pipe branches

In the real lens the end plugs will have beryllium inserts pressed into the titanium shell as is shown in Figs. 1 and 3. Since the production of beryllium inserts and vacuum welding of details with beryllium is quite dangerous and expensive procedure, it could delay substantially the manufacture of the lens designed for primary tests. Therefore, at the first stage of the lens development they were manufactured with the end plugs of stainless steel (titanium).

The technology and reliability of welding the end plugs worked out at a special stand simulating the geometry of lens end with holes (5) for tightening bolts (Fig.14). The plug (3) was inserted into the body hole (1) with the thermal compression method. The plug was manufactured with a diameter larger than the body hole diameter by $\Delta = 0.1\ mm$ and prior to pressing it was cooled down to temperature of liquid nitrogen and the body was heated up to temperature of $300\,^{\circ}C$. After this, an electric-arc welding is performed (in case of titanium, in a neutral gas). The model manufactured in this way was tested by applying into cavity (2) oil at a pressure of $P = 1400\ atm$. In this case, the welding joint was not destroyed but the stainless steel body was stretched in radial direction.

The end plugs in the lens were pressed and welded by the same technology.

The next operation was welding of supplying pipes (pos.3 in Fig.3) with an electric-arc welding.

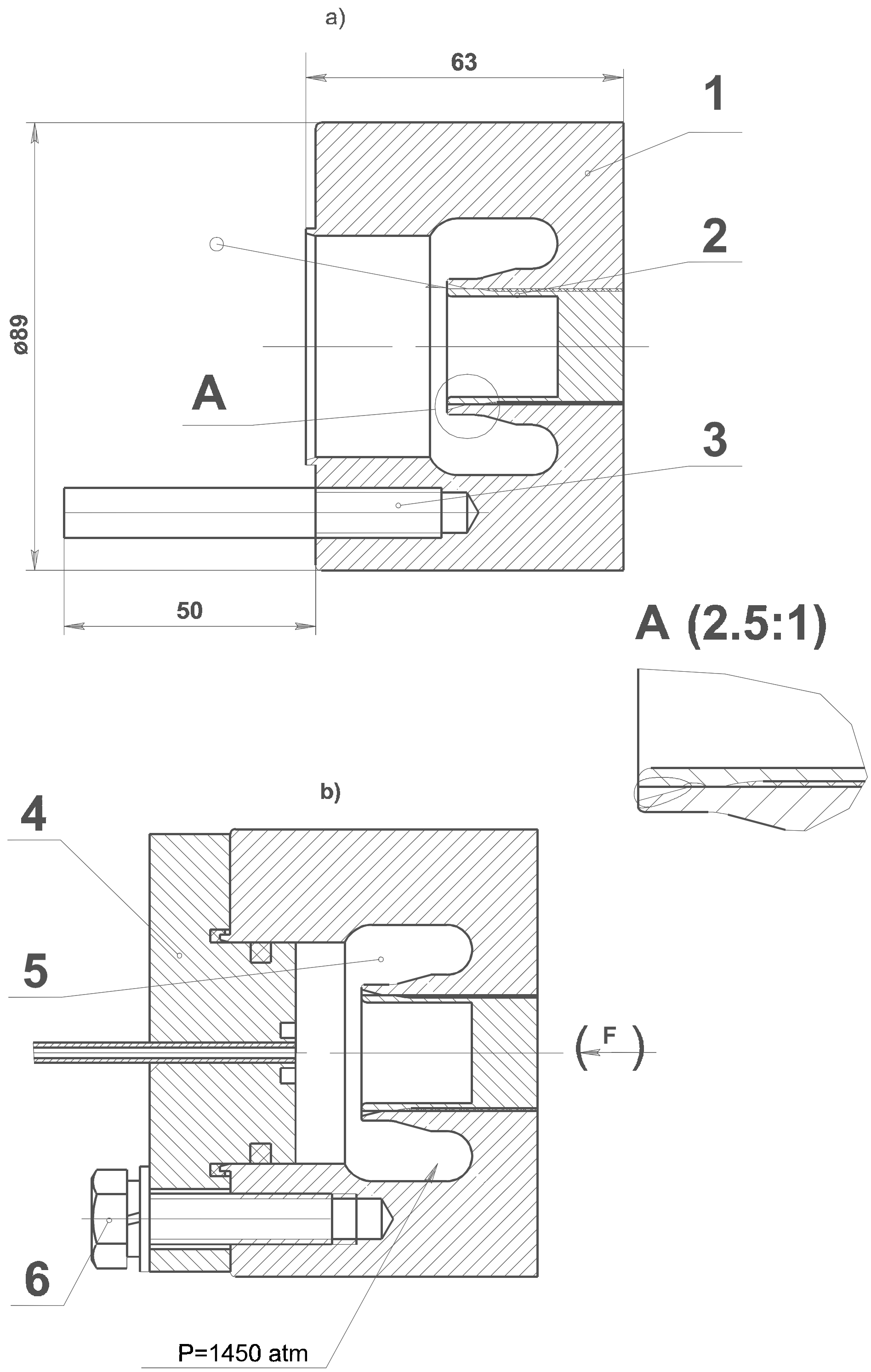

Fig.13. Samples for worked out welding regime (a) and for welding tested (b).

1 – sample body; 2 – ceramic coating; 3 – pins; 4 – plug; 5 – oil cavity; 6 – tightening bolts.

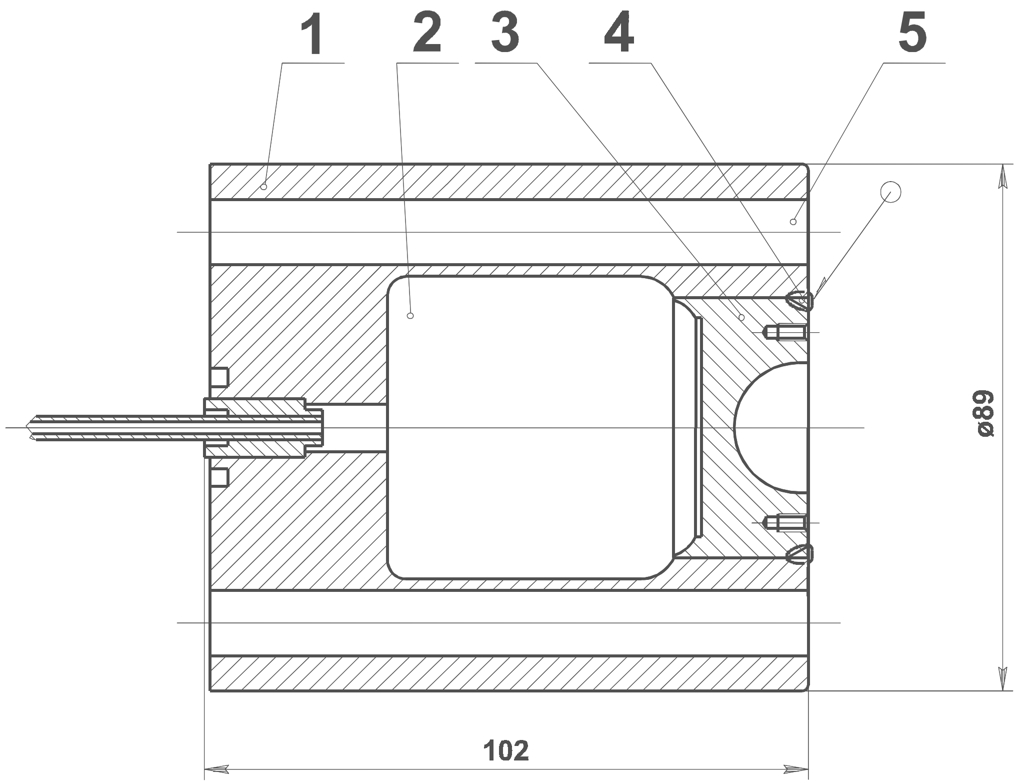

Fig. 14 Sample for end plugs welding reliability test.

1 – body; 2 – oil cavity; 3 – end plug; 4 – welding; 5 – holes for tightening bolts.

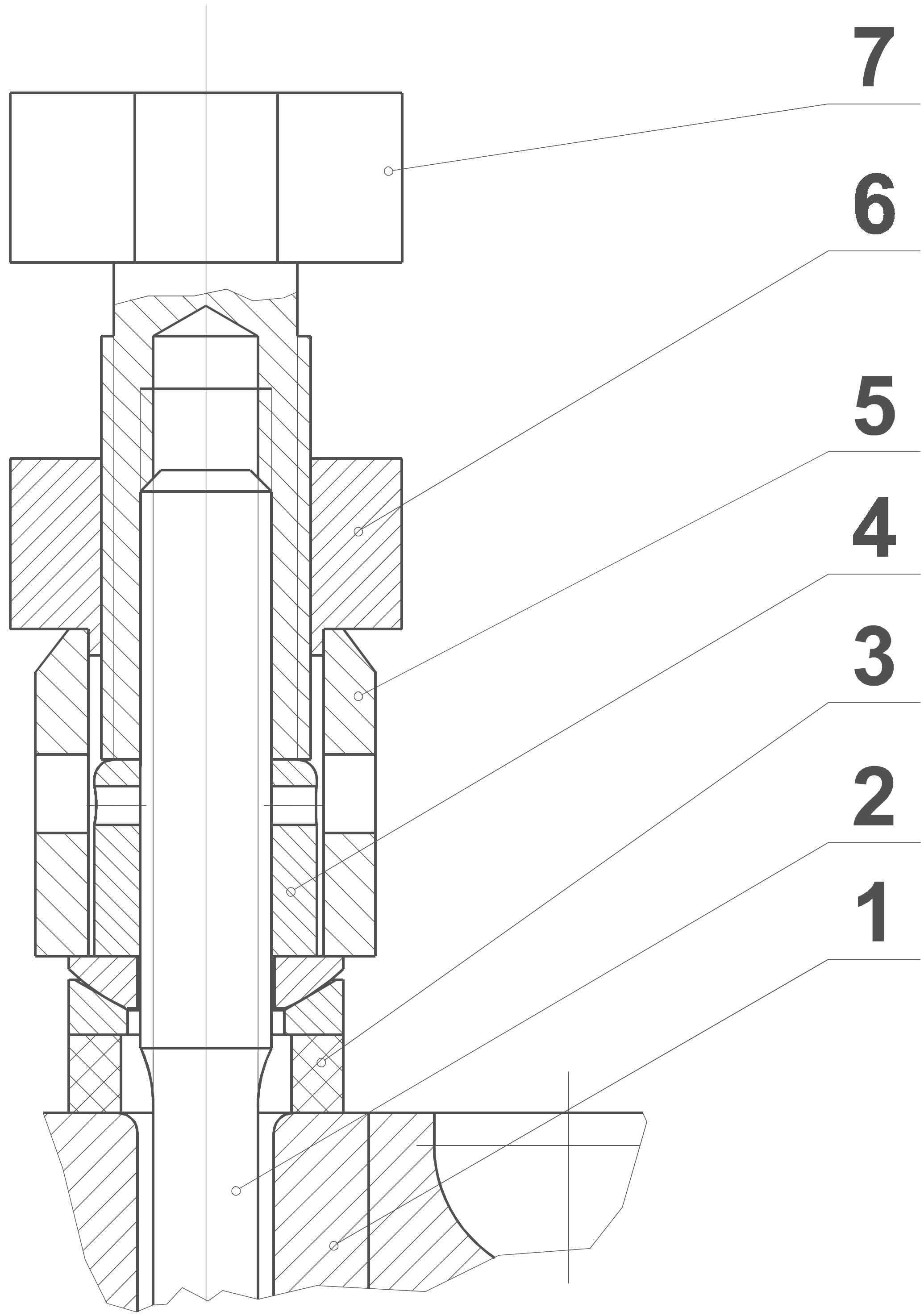

Fig. 15. Technological scheme of long pins tighten.

1 – lens body; 2 – pin; 3 – ceramic washer; 4 – main nut; 5 – support; 6,7 – tightening nut and bolt.

4) Lens longitudinal tightening

At electron-beam welding of the central pipe, electric-arc welding of the end plugs and after lens annealing it was subjected to heating up high temperature. Therefore, during these procedures, long titanium pins providing the main tightening of bodies in the longitudinal direction remained untightened to avoid their stretch during the heating up to high temperature. After the completion of welding and annealing these pins are tightened with the use of isolating ceramics washers (pos.2 in Fig. 15) by special technology providing maximum tightening of pins an enabling one to avoid their twisting in the process of tightening. For this aim, a special device (Fig.15) was used. At simultaneous tightening of nuts (6 and 7) the twisting momentum is eliminated and the long pin is tightened with a force of *2000 kG* leading to its elastic stretch by 0.45 *mm*. In this case, the mechanical stress in the pin material reaches = $4000\ kG/cm^2$ admissible for the VT-6 titanium alloy. After this, the main nut (5) is tightened without significant force and the technological nuts (3 and 4) are unscrewed and excessive part of a pins (6) is cut. Such a way of pin tightening enables one to produce the total force of axial tightening of bodies of $F = 2000 \times 12 = 24000\ kG$.

Photo at Fig.16 a,b,c,d show the lens in the process of assembly and putting into the transformer. Photo at Fig. 17 a,b shows the lens connected with transformer and lithium system.

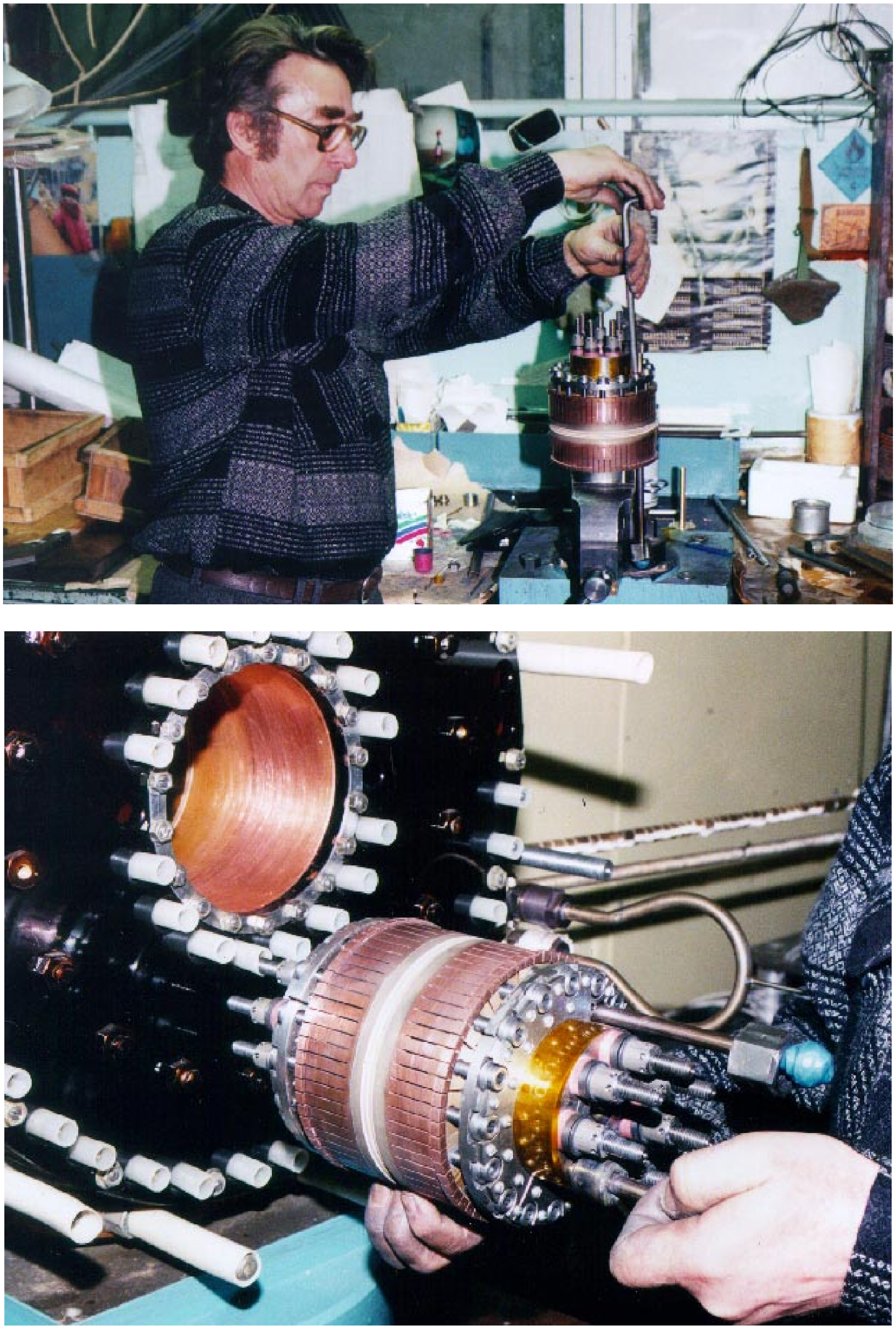

Fig. 16a,b. Photo of the lens in process of assembling (a) and installation in to the transformer (b)

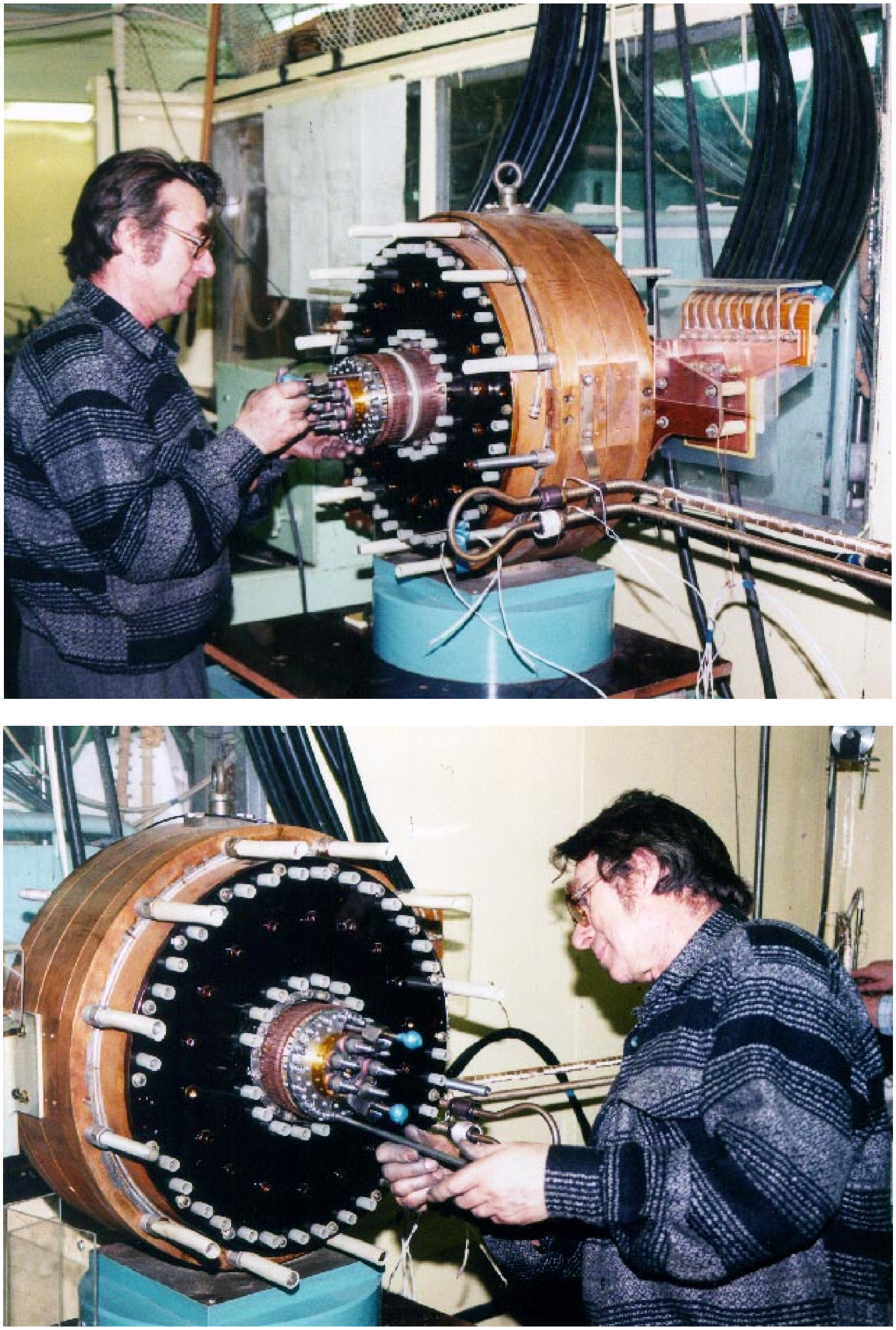

Fig. 16c,d. Photo of the process of the lens installation in to the transformer

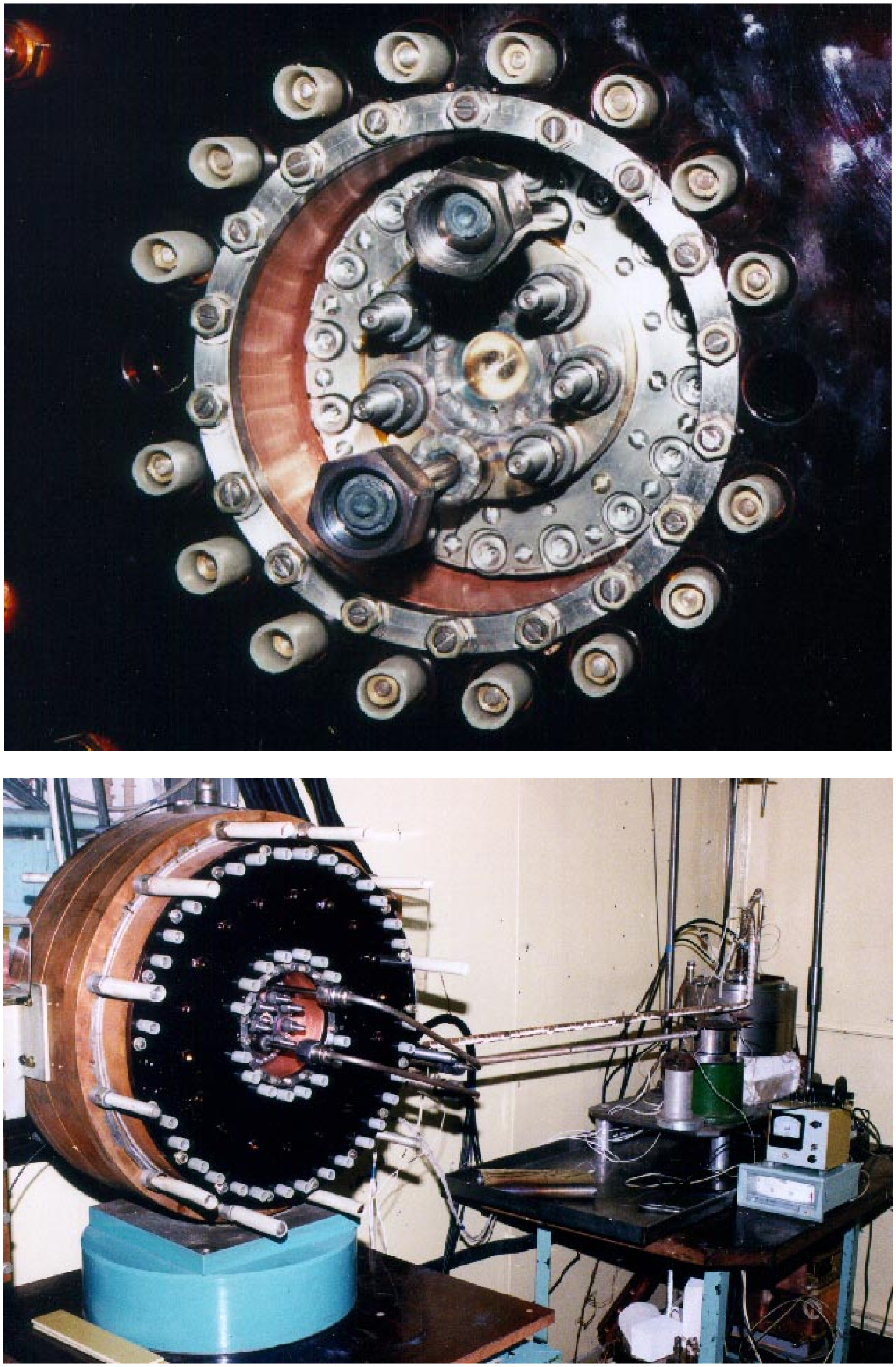

Fig. 17a,b. Photo of the lens connected with transformer (top) and connected with lithium system (bottom)

III. References

1. B.F.Bayanov, et al. “Liquid Lithium Lens for Fermilab Antiproton Source”. Preprint BINP 98–23, Novosibirsk, 1998.
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